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[1] In this paper, we show that a linear, continuously stratified ocean model reproduces observed wind-driven intraseasonal sea level variability in the coastal waveguide of the Northern Indian Ocean (NIO). Sensitivity experiments with intraseasonal wind forcing selectively applied in the equatorial region, Bay of Bengal, and Arabian Sea show that a large part of the basin-scale sea level variations are driven by zonal wind fluctuations along the equator. Within the NIO coastal waveguide, the contribution of remote equatorial forcing decreases from ~80–90% in the Andaman Sea to ~50% northeast of Sri Lanka and then increases to ~60–70% along the west coast of India. During the southwest monsoon, intraseasonal wind variations become stronger over the NIO, resulting in a larger contribution of local wind forcing to sea level variability along the west (up to 60%) and east (up to 40%) coasts of India. **Citation:** Suresh, I., J. Vialard, M. Lengaigne, W. Han, J. McCreary, F. Durand, and P. M. Muraleedharan (2013), Origins of wind-driven intraseasonal sea level variations in the North Indian Ocean coastal waveguide, *Geophys. Res. Lett.*, *40*, doi:10.1002/2013GL058312.

1. Introduction

[2] The Asian continent bounds the Indian Ocean to the north. This distinct geographical setting drives the strongest monsoon on Earth, associated with seasonally reversing winds. These wind variations drive seasonal equatorial Kelvin and Rossby wave responses. The seasonal equatorial Kelvin waves propagate into the North Indian Ocean (hereafter NIO) as coastal Kelvin waves [*McCreary et al.*, 1993]. As a result, both local and remote forcing shape the seasonal variations of the East India Coastal Current [*Shankar et al.*, 1996; *McCreary et al.*, 1996]. A similar remote influence of equatorial wind forcing on the NIO sea level variability has also been demonstrated at interannual [e.g., *Han and Webster*, 2002] and decadal [*Nidheesh et al.*, 2013] timescales.

[3] Indian Ocean winds also exhibit strong variability at intraseasonal timescales. In boreal winter, those wind variations are the strongest between the equatorial strip and southern tropics. They are associated with the Madden-Julian oscillation (hereafter MJO) [*Zhang*, 2005], a basin-scale atmospheric convective perturbation with ~30–80 day timescales. In boreal summer, intraseasonal variability (hereafter ISV) shifts northward and is associated with active and break phases of the Indian summer monsoon with ~30–60 day timescales [e.g., *Goswami*, 2005].

[4] The MJO and active/break monsoon phases both have equatorial signatures, inducing ISV in the equatorial zonal wind field throughout the year. The equatorial oceanic response to that wind variability has been described in many articles [e.g., *Masumoto et al.*, 2005; *Sengupta et al.*, 2007; *Iskandar and McPhaden*, 2011; *Nagura and McPhaden*, 2012]. On the other hand, only a few papers have focused on NIO oceanic ISV. *Durand et al.* [2009] attributed ISV along the east coast of India to mesoscale eddies, which indeed contribute to variability in the interior Bay of Bengal [e.g., *Cheng et al.*, 2013]. Using satellite observations, *Vialard et al.* [2009] showed that the intraseasonal equatorial Kelvin waves propagate into the NIO in the form of coastal Kelvin waves. This study established a clear link between the equatorial and coastal waveguides in the NIO at intraseasonal timescales, as was earlier demonstrated at lower frequencies. Analysis of current meter measurements on the west coast of India indicated that remote forcing contributes significantly to the variability of observed currents at intraseasonal timescales [*Shetye et al.*, 2008; *Amol et al.*, 2012]. *Girishkumar et al.* [2013] further suggested that remote equatorial winds could also significantly influence intraseasonal thermocline variations observed in the interior of the Bay of Bengal, especially in the low-frequency tail of the intraseasonal band. These studies, however, did not precisely quantify the relative effects of remote and local forcing, particularly within the NIO coastal waveguide.

[5] In this paper, our objective is to quantify the relative contributions of remote forcing from the equator and local forcing in the Bay of Bengal and Arabian Sea to intraseasonal sea level variations in the NIO coastal waveguide. In section 2, we describe the linear ocean model and the sensitivity experiments that allow us to evaluate the aforementioned contributions. We quantify these contributions in section 3 and discuss their seasonality along the Indian coast. Section 4 provides a summary and discussion.

2. The Linear Continuously Stratified Ocean Model

[6] We use a modified version of the linear, continuously stratified ocean model presented in detail in *McCreary et al.* [1996]. Solutions are represented as a sum of vertical

Additional supporting information may be found in the online version of this article.

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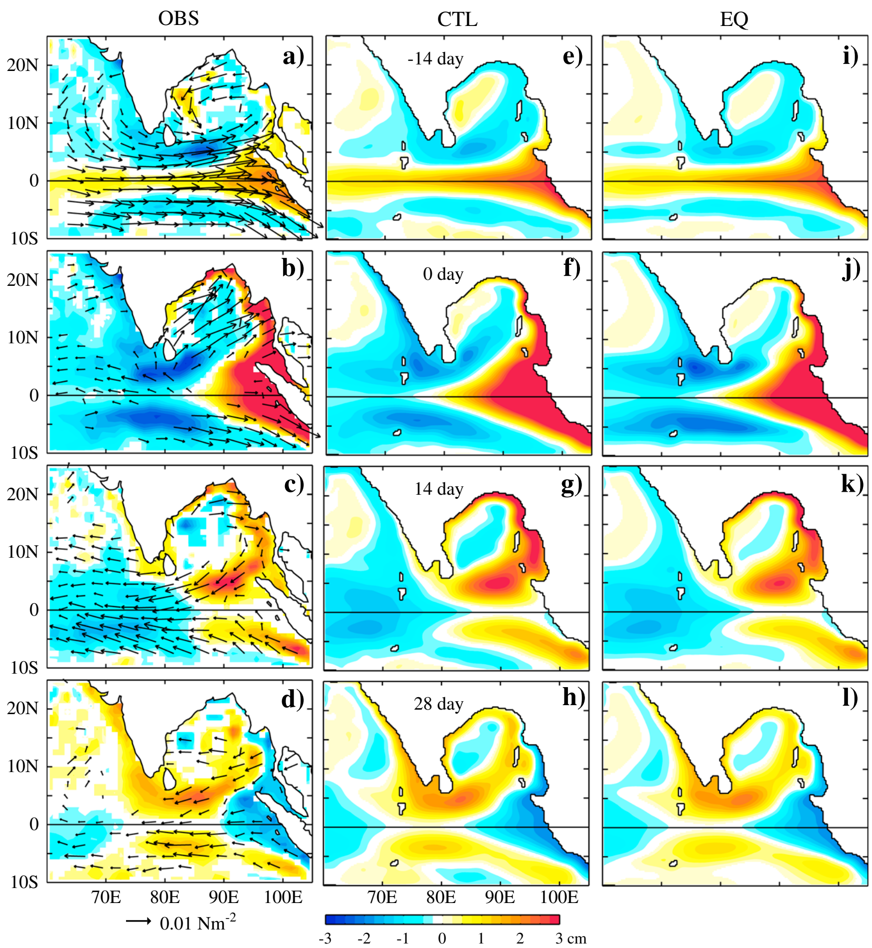

Figure 1. Lag regression (Lags indicated on the middle column) of 20–150 day filtered QuikSCAT wind stress (first column) and sea level to the normalized principal component of the first EOF of 20–150 day filtered sea level in (a–d) observations (17% of total variance, second mode 6%), (e–h) CTL experiment (44% of total variance, second mode 14%), and (i–l) EQ experiment (49% of total variance, second mode 15%). The regression at lag 0 in Figures 1b, 1f, and 1j shows the spatial structure of the first EOF. Values that are not statistically significant at the 95% confidence level are masked (significance tests in this figure and Figure 3 use a standard *t* test, with 1 degree of freedom per 70 days of data, as determined from the lagged autocorrelation of the principal component used for the regression).

normal modes, and are obtained numerically on a 0.25° regular grid over the 30°S–30°N, 30°E–110°E domain, with a coastline determined from the 200-m isobath. The model is forced by intraseasonal (20–150 day filtered) daily Quick Scatterometer (QuikSCAT) wind stresses (available from http://cersat/ifremer.fr/data/) from August 1999 to October 2009. Several studies indicate that this wind stress product yields a realistic intraseasonal oceanic response in the equatorial Indian Ocean [e.g., *Sengupta et al*., 2007; *Nagura and McPhaden*, 2012]. We show results obtained using five baroclinic modes but find, as in *Nagura and McPhaden* [2012] (see supporting information), that the first two vertical modes dominate the equatorial sea level solution, while the first mode dominates the sea level solution north of 15°N in the NIO coastal waveguide. More details on the model are provided in the accompanying supporting information.

[7] We refer to the above solution as the control (CTL) experiment. To assess the relative importance of wind forcing in the equatorial (EQ), Bay of Bengal (BoB), Arabian Sea (AS), and southern Indian Ocean (SIO) regions, we perform sensitivity experiments by applying intraseasonal wind forcing only in each of those basins. The EQ region is bounded by 5°N and 5°S; the BoB and AS are confined to the north of 6°N and divided at 79.75°E; the SIO is confined to the south of 6°S (see Figure 2). The forcing in each sensitivity experiment is ramped down to zero within 1° of the borders of the forcing region, and the sum of all the forcings (i.e., EQ + BoB + AS + SIO) is equal to the forcing of CTL experiment. The linearity of the model then ensures that the sum of the sensitivity experiments is equal to the CTL solution.

[8] We use 0.25° weekly sea levels (obtained from www.aviso.oceanobs.com/fr/accueil/index.html) to validate the model. Intraseasonal signals are obtained by applying a 20–150 day band-pass filter, after removing the mean seasonal cycle computed from the first four harmonics. All analyses are based on 2001–2008 period (i.e., eight consecutive full years, after discarding the initial 1.5 years for adjustment of the model solutions).

3. Results

[9] An empirical orthogonal function (EOF) analysis allows the main large-scale intraseasonal sea level pattern to be extracted in the model and observations. The first

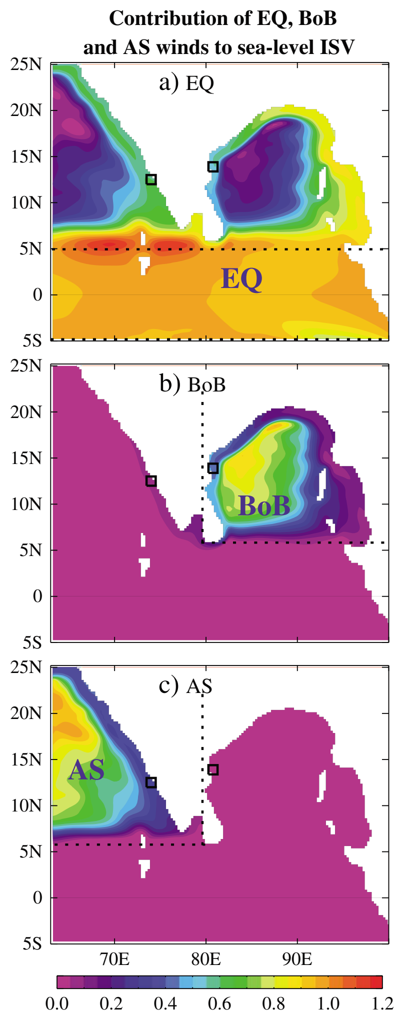

Figure 2. Contribution of wind forcing in the (a) equatorial waveguide, (b) Bay of Bengal, and (c) Arabian Sea to intraseasonal sea level variations, computed as the regression coefficients of 20–150 day filtered sea level of EQ (Figure 2a), BoB (Figure 2b), and AS (Figure 2c) experiments to those of CTL experiment. The sum of the contributions is equal to 1 by construction (the southern Indian Ocean contribution is negligible in the NIO). The dotted lines indicate the boundaries of the domain in which the EQ, BoB, and AS forcing are applied.

EOF is well separated from the rest of the variability in both observations (17% for first EOF shown in Figure 1b, 6% for the second) and CTL experiment (44% for the first EOF shown in Figure 1f, 14% for the second). Thus, this EOF captures the dominant large-scale intraseasonal sea level signal throughout the basin. The explained variance is larger in our linear model than in observations because the model does not produce eddies. The correlation of the model and observed sea level first principal component is 0.89, indicating that the linear model captures the phase of the observed basin-scale sea level variability remarkably well.

[10] Figure 1 shows the wind stress and sea level patterns obtained from a lag regression to the principal components (time series) associated with the first EOF. These patterns are remarkably similar to those shown in *Vialard et al.* [2009] and *Iskandar and McPhaden* [2011] though we used different method of analysis, indicating the robustness of these patterns. Equatorial westerly wind stress anomalies force an equatorial downwelling Kelvin wave (Figures 1a and 1b) that reflects from the Sumatra coast as a downwelling equatorial Rossby wave (Figures 1c and 1d), with some of the energy propagating into and around the Bay of Bengal (Figures 1b and 1c) and up the west coast of India (Figure 1d) as coastal Kelvin waves. Figures 1e–1h show that the CTL experiment captures the observed patterns remarkably well, both near the equator and in the coastal waveguide.

[11] Most of the basin-scale variability is due to equatorial wind forcing, as shown by the good match in the basin-scale sea level pattern of the EQ solution with that of the observations and CTL (Figures 1i–1l). We further quantify the pointwise contribution of forcing in each region by computing the regression coefficient of sea level in each sensitivity experiment to that in CTL (Figure 2). Note that this regression allows a general evaluation of the contribution of forcing in various regions to sea level ISV, not only to those associated with the first EOF shown in Figure 1. The SIO solution is negligible and hence not shown. With contributions of more than 95% (Figure 2a; coefficient values > 0.95), EQ wind forcing explains most of the sea level ISV within the equatorial waveguide, as has already been demonstrated in previous studies [e.g., *Nagura and McPhaden*, 2012]. The ISV amplitude of the EQ solution is larger than that of CTL near 5°N on both sides of the Maldives archipelago (values slightly larger than 1 in Figure 2a). This feature is due to spurious Ekman pumping that occurs because ramping of the wind at 5°N in EQ artificially increases the wind stress curl, but it has a negligible effect on our results (other solutions with a less abrupt ramping at the edge of the equatorial waveguide show qualitatively similar contributions).

[12] The EQ contribution also dominates the solution in most of the NIO coastal waveguide. Around the rim of the Bay, the EQ contribution decreases from ~80–90% near Myanmar and in the northern Bay down to ~50% north of Sri Lanka (Figure 2a). EQ forcing contributes to ~60–70% of the intraseasonal sea level variations along the west coast of India.

[13] The EQ contribution expands westward offshore into the Bay of Bengal and Arabian Sea up to ~15°N but is largely confined to the coast farther northward (Figure 2a). This trapping happens because first-baroclinic-mode Rossby waves exist only at periods longer than ~95 days north of 15°N [*Vialard et al.*, 2009], whereas the signals that originate from the equator have shorter periods [*Han*, 2005]. The progressive westward increase of the BoB and AS wind forcing to sea level ISV in the basin interiors (Figures 2b and 2c) is due to the contribution of local wind forcing to the Rossby waves as they propagate westward.

[14] Wind stress variations within the Bay contribute to sea level variations along the east coast of India through two processes: (a) the arrival of Rossby waves generated in the basin interior and (b) the forcing by alongshore winds in the coastal waveguide. The southward increasing contribution of BoB forcing along the east coast of India (Figure 2b) is likely due to a combination of those two processes. On the other hand, wind variations in the AS can only contribute to sea level ISV along the west coast of India through alongshore winds. The relatively constant value (~30%) of the AS contribution all along the west coast (Figure 2c) suggests that most of this alongshore wind forcing occurs near the southern tip of India.

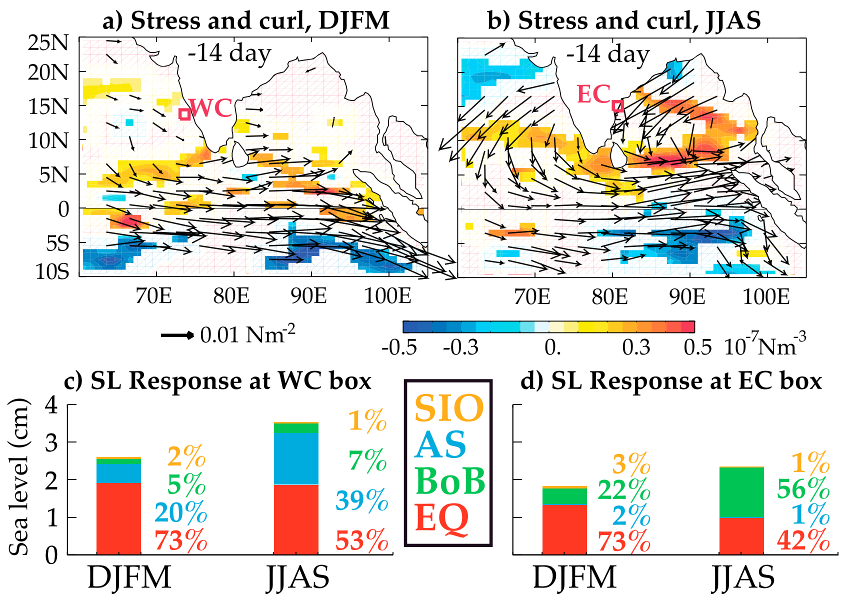

Figure 3. The 20–150 day filtered QuikSCAT wind stress (vectors) and wind stress curl (colors) regressed to the normalized first principal component of 20–150 day filtered observed sea level at 14 day lead, for (a) December–March and (b) June–September. Decomposition of 20–150 day sea level standard deviation (cm, also indicated as a %) in the (c) WC (west coast; 73.5°E–74.5°E, 12°N–13°N, cf. Figure 3a) and (d) EC (east coast; 80.5°E–81.5°E, 13°N–14°N; cf. Figure 3b) boxes into contributions from equatorial (red), Bay of Bengal (green), Arabian Sea (blue), and South Indian Ocean (orange) wind forcing, for DJFM and JJAS. The −14 day lag was selected for this plot, because it is associated with the largest wind stress and wind stress curl perturbations.

[15] Figure 3 shows the wind patterns associated with Northern Hemisphere (a) winter and (b) summer basin-scale sea level ISV. The patterns are remarkably similar to the dominant modes of atmospheric variability: MJO in winter [e.g., *Zhang* [2005]] and active/break monsoon phases in summer [e.g., *Goswami* [2005]]. While wind stress amplitude does not change much at the equator between the two seasons, it does become much larger over the NIO during summer (Figures 3a and 3b). Wind stress curl is strong in the central and southern Bay of Bengal, and the alongshore wind stress is strong along the western rim of the Bay (Figure 3b). In the Arabian Sea, the winds are generally oriented perpendicular to the coast, except close to the southern tip of India and Sri Lanka where they have a larger alongshore component, which is also associated with larger curl (Figure 3b).

[16] The amplitude of the equatorial, remotely driven, sea level ISV on both coasts of India does not change much between winter and summer (red bars on Figures 3c and 3d). Along the west coast of India, there is a large increase of wind-driven, sea level ISV in summer (blue bars, Figure 3c), likely linked to the larger alongshore wind stress and curl variations close to the southern tip of India (Figure 3b). The WC box is representative of the west coast of India: the relative contributions of EQ and AS forcing do not vary much along this coast (not shown).

[17] On the east coast of India, there is also a summertime increase of the contribution in the Bay of Bengal forcing to sea level variations (green bars, Figure 3d). Alongshore wind stresses (Figure 3b) force downwelling coastal Kelvin waves that reinforce the remotely driven sea level tendency (Figures 1i and 1j), while Ekman pumping in the central and southern Bay (Figure 3b) forces upwelling Rossby waves with the opposite contribution. Thus, the overall positive contribution of BoB forcing is due to the dominance of alongshore stresses along the western rim of the Bay. Similar analysis at other locations in the BoB coastal waveguide also indicates larger contribution of local forcing in summer. This contribution, however, diminishes when moving clockwise around the rim of the Bay.

[18] The larger wind forcing results in larger variability (standard deviation) in NIO sea level during summer on both coasts of India (Figures 3c and 3d), with the proportion of regionally forced to total sea level variability increasing from ~20% to ~40% on the west coast and up to ~60% on the east coast.

4. Discussion

[19] The observed intraseasonal, basin-scale sea level patterns in the NIO identified by *Vialard et al*. [2009] are well reproduced by our wind-driven linear model. This validation gives us confidence to use the model to investigate the origins of wind-driven intraseasonal oceanic variations in the NIO, particularly in the coastal waveguide. Sensitivity experiments indicate that wind-forced sea level variations in the NIO coastal waveguide are dominated by the contribution of equatorial wind forcing. Around the rim of the Bay, this contribution decreases from ~80 to 90% in the Andaman Sea, to ~50% northeast of Sri Lanka and is ~60–70% along the west coast of India. The sea level variations along the coasts of Myanmar, Bangladesh, and west coast of India can therefore be predicted several weeks in advance from sea level in the eastern equatorial Indian Ocean. Along the east coast of India, eddy-induced ISV is large [e.g., *Durand et al*., 2009] and can sometimes dominate the wind forced signal.

[20] Our results further illustrate that the equatorial wind contribution to NIO sea level variations is modulated seasonally. The northward shift of the atmospheric ISV in summer induces larger fluctuations of alongshore wind stress on the western rim of the Bay and close to the southern tip of

India. This increase results in larger sea level ISV, and a larger contribution of BoB and AS winds to this ISV, on both coasts of India during boreal summer.

[21] Several previous studies [e.g., *Han*, 2005; *Iskandar and McPhaden*, 2011; *Girishkumar et al.*, 2013] have noted that the ocean's response to ISV forcing amplifies at longer periods (near 90 day) than the forcing itself (near 30–60 day). In this study, we chose to analyze these two frequencies together by using a 20–150 day filter, but the contributions of the various basins remain qualitatively similar when those two periods are considered separately (see supporting information).

[22] In the Bay of Bengal interior, *Girishkumar et al.* [2013] and *Cheng et al.* [2013] suggested a significant contribution of equatorial remote forcing. We consistently find that the equatorial solution contributes between 40 and 60% of the sea level ISV at the locations analyzed by *Girishkumar et al.* [2013] (see supporting information). Our results are also consistent with those of *Shetye et al.* [2008] and *Amol et al.* [2012], who suggested that remote forcing from farther south influences current variations along the west coast of India.

[23] To our knowledge, the present study is the first one to quantify the relative contributions of intraseasonal forcing in various regions of the Indian Ocean to wind-driven sea level ISV in the NIO coastal waveguide. Some issues, however, remain unresolved. Is alongshore wind stress ISV near the southern tip of India and along the western rim of the BoB the main source of coastal sea level local forcing in summer, as suggested by this study? Is there vertical propagation of energy at intraseasonal timescales in the coastal waveguide, as suggested by *Nethery and Shankar* [2007] and *Amol et al.* [2012]? These topics will be investigated in a future study.

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